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(54) Ophthalmological lasers

(57) The present invention relates to a laser device for surgical treatment of ametropia and which makes use of substantially all of the available radiation, comprising the following components arranged on a common optical axis: a pulsed laser 1, a unit 3 for uniform distribution of laser radiation energy density over the beam cross-sectional area, a shaper 6 of required distribution of laser radiation energy density over the beam cross-sectional area, and a projecting lens 7, wherein the unit for uniform distribution of radiation energy density is a rectangular cross-section waveguide 5, preferably shaped as a parallelepipped, in which case a lens may be placed before it along the pathway of laser radiation, or it may also be shaped as a pyramid frustum. The device may include a vibrator 9.

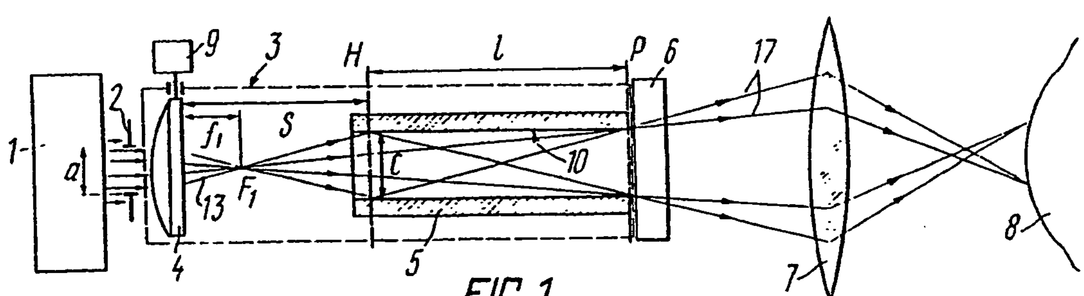

FIG. 1

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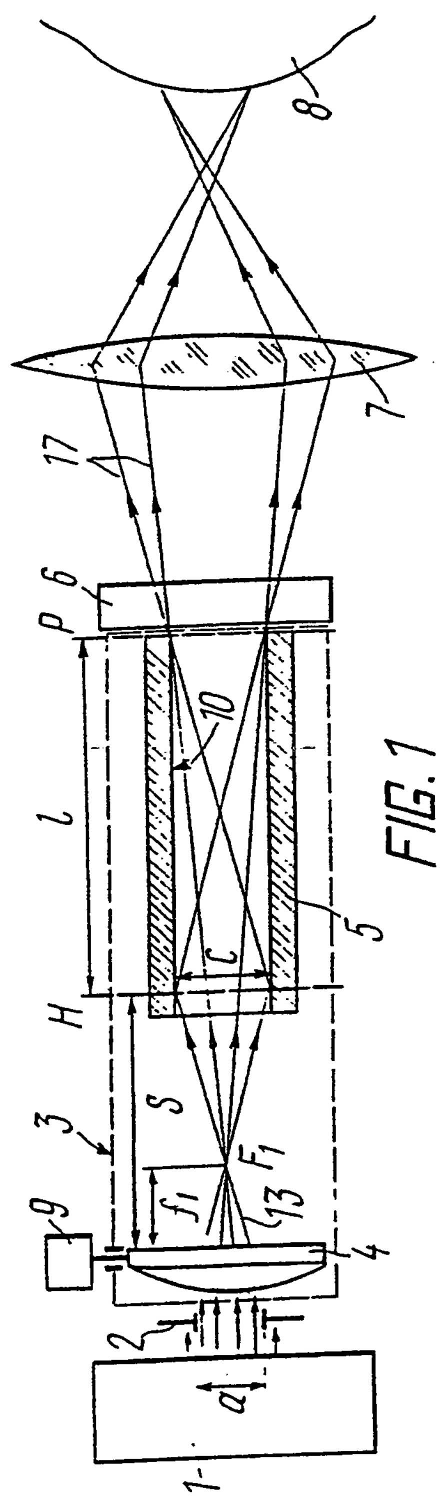
8
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FIG.1

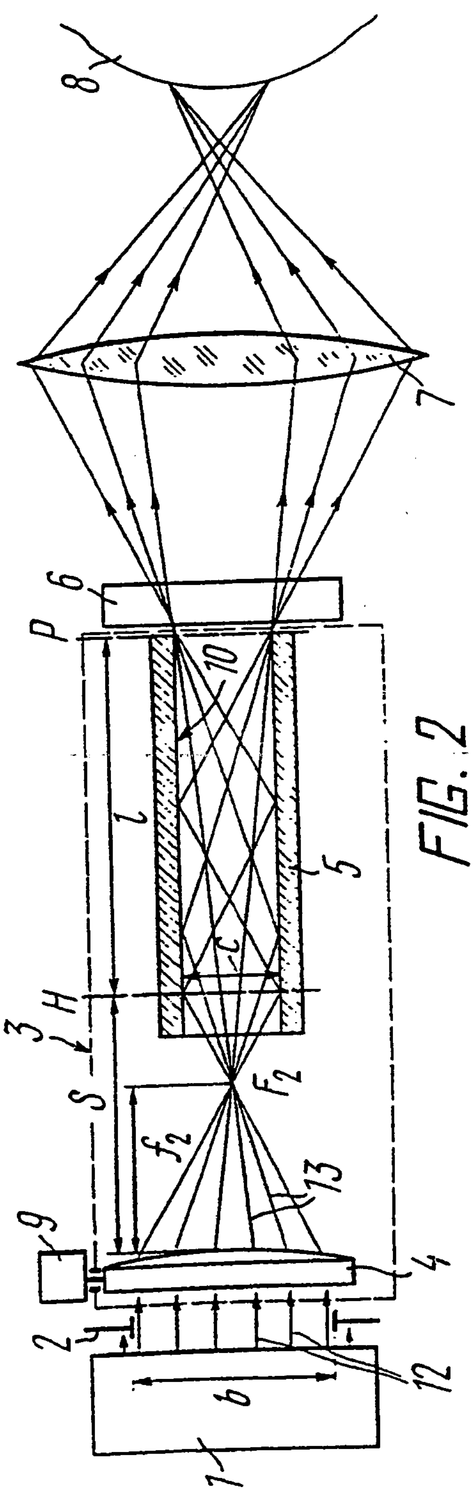
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FIG. 2

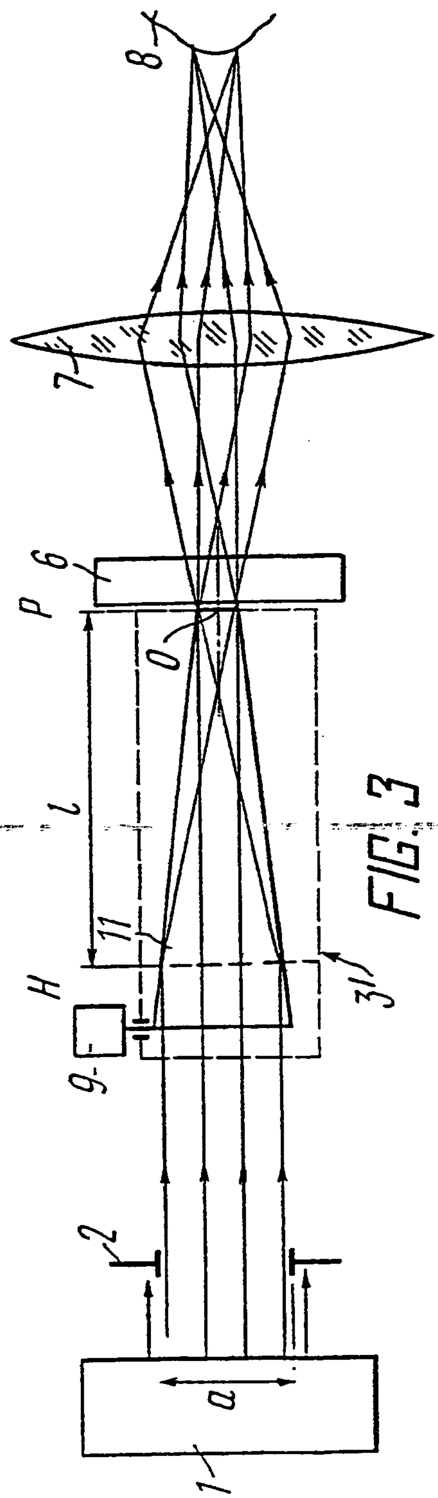

FIG. 3

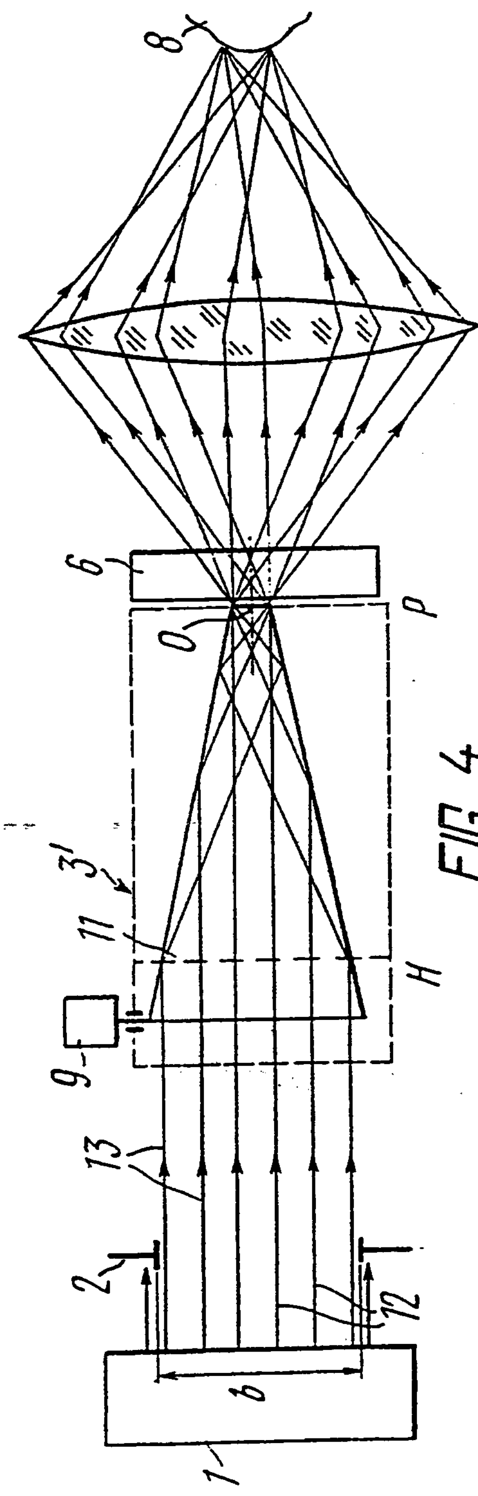

FIG. 4

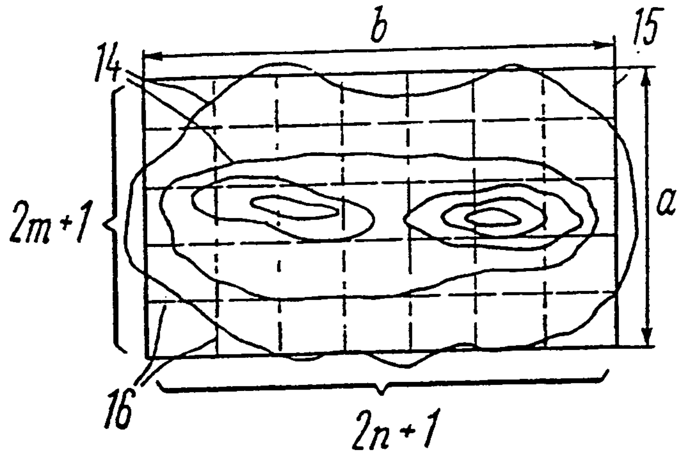

FIG. 5

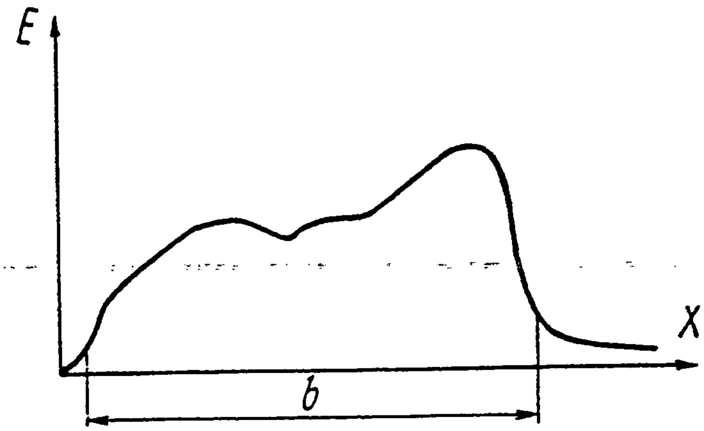

FIG. 6

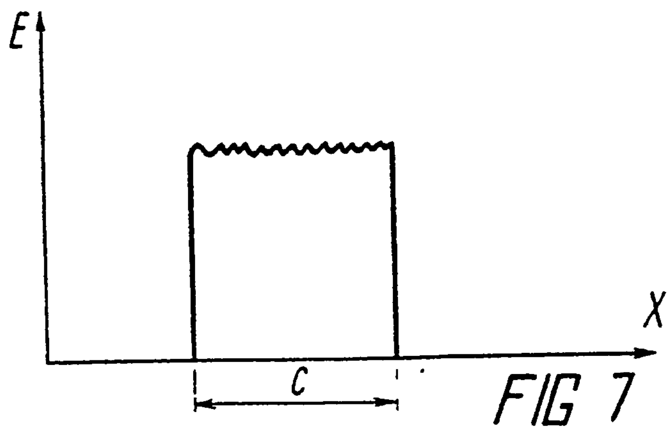

FIG 7

Ophthalmological Lasers

The invention relates generally to medicine, more specifically to ophthalmology and has particular reference to a device for surgical treatment of ametropia.

At present laser methods of treatment are being adopted in worldwide ophthalmosurgical practice, in particular, laser-assisted methods for correction of eye refraction anomalies by virtue of radiation emitted by UV excimer lasers. The most urgent problem encountered in engineering laser ophthalmosurgical units aimed at the aforésaid purposes is to attain a required profile of irradiation applied to the cornea, for which prupose the output laser radiation should feature a smooth symmetrical distribution of energy density over the beam cross-sectional area, predominantly a rectangular (uniform) distribution. However, the distribution energy density in excimer lasers is not such which renders the problem of how to transform nonuniform and unsymmetrical distribution of laser radiation into a uniform distribution the most urgent one.

One state-of-the-art device for surgical treatment of ametropia is known to comprise the following components arranged on a common optical axis: a UV pulsed laser, a unit for uniform distribution of laser radiation energy density over the beam cross-sectional area, a shaper of

a required distribution of laser radiation energy density over the beam cross-sectional area, and a projecting lens (cf.SPIE, vol.908, Laser Interaction with Tissue, 1988, by P.R.Ioder at al., "Beam delivery system for UV laser ablation of the cornea", pp.77-82).

In said device the unit for uniform distribution of laser radiation energy density is made as a rotating system of mirrors similar, as to its effect, to the Dove prism known in optics. Uniform distribution of laser radiation energy density over the beam cross-sectional area is attained by rotating the beam as a whole round its optical axis. In this case nonuniform distribution remains in each separate radiation pulse and uniformity occurs in time as a result of averaging a train of consecutive radiation pulses. Such uniformity of distribution with the aid of the known system is effective only for lasers which feature energy density distribution over the beam cross-sectional area as smooth and monotonous. Thus, to provide uniform density distribution, in the presence of drastic excursions in distribution, which is practically the case in all actual lasers, can be only by cutting off part of the laser beam, wherein energy distribution is loose and monotonous. However, this results in bad energy losses, affected accuracy and prolonged time of the operative procedure.

Thus the present invention provides a device for ophthalmological laser surgery comprising a laser source, a beam distributor and a projecting lens, wherein the distributor comprises a waveguide. The waveguide preferably has a rectangular cross-section, and will be in the form of a parallelipiped, or a pyramidal frustum with the greater base facing the laser source.

In particular, it is preferred that the distributor further comprises a lens to focus the laser emission into the the waveguide, and preferably which can oscillate normal to the path of laser emission. Generally, the focussing lens used will have different focal lengths in the meridional and sagittal planes.

Alternatively, where the waveguide is in the form of a pyramidal frustum, the apex of the waveguide may be adapted to oscillate about the path of laser emission. Such oscillation of lens or frustum is advantageous to provide even distribution of the laser emission over the surface of the eye.

The device according to the invention will generally further comprise a beam shaper.

The invention also provides that in a device for surgical treatment of ametropia, comprising the following components arranged in succession on a common optical axis: a UV pulsed laser, a unit for uniform distribution of laser radiation energy density over the beam cross-sectional area, a shaper of a required distribution of laser radiation energy density over the beam cross-sectional area, and a projecting lens, according to the invention, the unit for uniform distribution of laser radiation energy density is shaped as a rectangular cross-section waveguide.

The waveguide may be also be shaped as a square cross-section parallelepiped and an additional lens may be placed ahead of it as along the pathway of laser radiation.

In this case it is also desirable that the additional lens be capable of oscillating in a plane square with the optical axis.

The waveguide may be shaped also as a frustum of a pyramid which faces with its greater base the laser.

In this case it is expedient that the pyramid be capable of oscillating round the geometric centre of the lesser base thereof in two mutually square directions normal to the optical axis.

The device for surgical treatment of ametropia, according to the present invention, features practically complete utilization of laser energy and arbitrary distribution of radiation energy density at its output and enables one to substantially enhance accuracy of surgery and to curtail the operating time at least two times.

Furthermore, the device, according to the invention, is constructionally simpler than the heretofore-known device of similar application.

In what follows the invention is illustrated in a detailed description of some specific exemplary embodiments thereof with reference to the accompanying drawings, wherein:

FIG.1 is a schematic side view of an embodiment of a device for surgical treatment of ametropia provided with a waveguide shaped as a parallelepiped, according to the invention;

FIG.2 is a plan view of FIG.1;

FIG.3 is as a side view of a device of FIG.1 provided with a waveguide shaped as a frustum of a pyramid;

FIG.4 is a plan view of FIG.3;

FIG.5 shows a pattern of a laser beam split into separate portions in the waveguide;

FIG.6 is a distribution curve of laser radiation energy density E (plotted as ordinate) along a direction X (appearing as abscissa) square with the axis of the beam emergent from the laser; and

FIG.7 is a view of FIG.5 at the waveguide exit.

The device for surgical treatment of ametropia as shown in FIGS 1 and 2 comprises the following components arranged in succession on a common optical axis: a UV pulsed laser 1, a rectangular cross-section diaphragm 2, a unit 3 for uniform distribution of energy density of radiation emitted by the laser 1 over the beam cross-sectional area, said unit incorporating an additional lens 4 placed past the diaphragm 2 as along the pathway of radiation emitted by the laser 1, a rectangular cross-section waveguide 5 situated past said additional lens 4, a shaper 6 of a required distribution of laser radiation energy density over the beam cross-sectional area, and a projecting lens 7 which directs the laser radiation onto a patient's cornea 8.

The additional lens is capable of oscillating in a plane square with the optical axis in two mutually square directions independently, for which purpose the lens mount is associated with the output member of a mechanical vibrator 9.

The lens 4 has different focal lengths f_1 and f_2 in the meridional and sagittal planes, respectively (appearing as focal spots F_1 and F_2 in the Drawings) and its curved surfaces are in fact crossed cylinders.

The waveguide 5 in a given embodiment is in effect a square cross-section hollow parallelepiped, the inner

surfaces 10 of the walls of said parallelepiped having a mirror reflecting coating.

Used as the shaper 6 may be a variable-section circular diaphragm, or a rotary disk with a preset-configuration slit, or else an optic cell featuring variable radiation absorption as over the cross-sectional area thereof.

The projecting lens 7 constructs the image of the plane P of the exit end of the waveguide 5 on the cornea 8.

Unlike the embodiment discussed above, the one presented in FIGS 3 and 4 features a unit 3' for uniform distribution of laser radiation energy density, being essentially a waveguide 11 shaped as a pyramid frustum which faces the laser 1 with its greater base. The pyramid is capable of oscillating round the geometric centre 'O' of the pyramid lesser base in two mutually square directions normal to the optical axis, for which purpose the greater pyramid base is associated with the output member of the mechanical vibrator 9. The pyramid (i.e., the waveguide 11) is a solid structure made of a material transparent to laser radiation, e.g., magnesium fluoride, while the outer pyramid surfaces are given a high optical quality finish by fine polishing.

The embodiment of the device for surgical treatment of ametropia as shown in FIGS 1, 2, according to the invention, operates as follow.

A radiation beam 12 emerging from the laser 1 passes through the rectangular cross-section diaphragm 2 having the following adjustable dimensions: height (a) and width (b). The diaphragm 2 cuts off a desirable portion of the radiation from the laser beam 12. Then a beam 13 passes through the lens 4 for its cross-sectional area and angular aperture to change. Having passed through the lens 4 the beam 13 is focussed in two focal planes at the focal distances f_1 and f_2. The beam 13 past the lens 4 features a variable rectangular cross-section whose dimensions depend on the distance S from the plane of the lens 4 to the plane H of observation. The cross-sectional height a' of the radiation beam 13 at a distance $S > f_1$ and the cross-sectional width b' thereof at a distance $S > f_2$ are as follows:

$$a' = (S - f_1)\frac{a}{f_1} \quad ;$$

$$b' = (S - f_2)\frac{b}{f_2} \quad .$$

In a given embodiment of the device $a' = b' = c$. In this case the extreme rays of the radiation beam 13 entering the waveguide 5 in the plane H of observation

at the distance $S = f_1 (\frac{c}{a} + 1) = f_2 (\frac{c}{b} + 1)$, are incident upon the walls of the mirror waveguide 5 having a cross-section of C x C, the exit end of said waveguide lying in the plane P spaced the distance apart from the plane H which equals the length of the working portion of the waveguide 5.

Provided that $\ell = n(S - f_1) = m(S - f_2)$, where n, m = 2, 4, 6 .... arbitrary even numbers, the radiation beam 13 entering the waveguide 5 is split into a system (n + 1), (m + 1) of elementary beams which experience different numbers of reflections from the walls of the waveguide 5. Each of said elementary beams fills the entire exit end of the waveguide 5.

An exemplary splitting of the incoming beam 13 into 35 elementary beams is shown in FIG.5, where n = 6, m = 4, while curves 14 present the areas of equal intensity of the beam 12 at the output of the laser 1, a line 15 indicates the boundaries of the beam 13 past the diaphragm 2, dotted lines 16 exhibit 35 elementary beams of the radiation beam 13, each of them being projected onto the exit end of the waveguide 5 (the plane P), thus filling said exit end completely.

Energy density distribution in the plane P of the exit end of the waveguide 5 is in effect an interference pattern resulting from interference of the radiation beams (n + 1), (m + 1).

Radiation intensity $\vec{E}^2$ effective at the point having the coordinates (X, Y) at the exit end of the waveguide 5 is equal to $\vec{E}_1^{\,2} + \vec{E}_2^{\,2} + \ldots \vec{E}^2_{(n+1)\cdot(m+1)} + \sum_{ij}^{i \neq j} \vec{E}_i \cdot \vec{E}_j$,

where E_1, E_2 ..... is the intensity of radiation at the point (X, Y) of the corresponding waves;

$\sum_{ij}^{i \neq j} \vec{E}_i \cdot \vec{E}_j$ are interference terms, each being directly proportional to cos δ_{ij},

where $\delta_{ij} = \frac{2\pi}{\lambda} \Delta ij$

Δij denotes an optical difference between the runs of the waves i and j;

λ is the radiation wavelength.

With the intensity distribution averaged with respect to the period t of the interference pattern, one obtains:

$$\vec{E}^2 = \vec{E}_1^{\,2} + \vec{E}_2^{\,2} + \ldots\ldots + \vec{E}_{(m+1)\,(n+1)},$$

since cos $\delta_{ij} = 0$.

Thus, energy density distribution at the exit of the waveguide 5, after having been averaged with respect to the period t of the interference pattern is in effect the sum of distribution values of the beams $(n + 1) \cdot (m + 1)$, which results in uniform distribution of radiation energy density. For instance, root-mean-square deviation of the energy density is reduced by $\sqrt{(n + 1) \cdot (m + 1)}$ times for random splitting of the

incoming beam 13 into $(n + 1) \cdot (m + 1)$ equal elementary beams.

Now let us estimate the period of an interference pattern.

For the sake of simplicity let us consider interference in a hollow waveguide of two beams, i.e., the beam that has passed through the device without being reflected from the walls and the other beam that has experienced one reflection. A distance between the adjacent intensity maxima, i.e., the period $t \approx \frac{[\ell + (S - f_1)]\lambda}{C}$. With $\ell \leqslant 300$ mm, $(S - f_1) \approx 50$ mm, $C \approx 7$ mm, $\lambda \approx 0.2\ \mu m$, the period t is $< 10\ \mu m$. An actual distance between the adjacent intensity maxima (minima) is substantially lower than the above value due to interference of a great many radiation beams featuring a broad range of differences in the run. An accurate calculatiion of interference pattern is very difficult, therefore let us assume the value of $t \approx 10\ \mu m$ as the upper estimation of the scale of interference inhomogeneity of radiation intensity distribution at the waveguide exit. The required averaging with respect to the low period t in the course an ophthalmosurgical procedure occurs automatically, since such a surgery consists of about 500 to 1000 pulses of the radiation emitted by the laser 1, during which there occurs complete smearing of the interference pattern due to accidental eye movements on account of intrinsic eyeball oscillations at a frequency of up to 300 Hz (ocular tremor) which are controlled neither by the

doctor nor by the patient, as well as due to patient's heart beats, respiration, vibrations of the unit itself, etc.

Regardless of the aforesaid factors complete averaging of the interference pattern occurs at the exit end of the waveguide 5 due to oscillations performed by the lens 4 in two mutually square directions.

For the abovesaid parameters of the unit 3 oscillations of the lens 4 with an amplitude exceeding 10 to 20 µm will lead to complete averaging of the interference patterns corresponding to consecutive radiation pulses and, besides, to smearing of acute radiation intensity outbursts (hot spots) of the laser 1.

FIGS 6 and 7 illustrates operation of the unit 3 for uniform distribution of radiation energy density, FIG.6 showing distribution of laser radiation energy density over the cross-sectional area of the beam 12 in the meridional plane, while FIG.7 shows such distribution at the exit of the waveguide 5 (in the plane P).

The radiation beam emergent from the exit end of the waveguide 5 passes through the shaper 6 of a required distribution of laser radiation energy density over the beam cross-sectional area, where the energy density of the radiation beam uniform in the plane P is transformed obeying the law necessary for carrying a given surgery. Used as the shaper 6 may be a variable-section circular diaphragm, a rotary disk having a preset-configuration slit, or else an optic cell featuring variable absorption

of radiation of the laser 1 as over the cross-sectional beam area. Further on the radiation beam 17 passes through the lens 7 and is projected onto the cornea 8 of the eye operated upon. The lens 7 is so disposed that the image of the plane P is constructed on the cornea 8.

An embodiment of the device presented in FIGS 3, 4 operates similarly to an embodiment shown in FIGS 1, 2, the sole difference residing in that the beam 13 after having passed the diaphragm 2 arrives immediately at the entrance of the waveguide 11.

Further on the radiation beam 13 passes through the waveguide 11 shaped as a square pyramid frustum having an entrance end measuring $a' \cdot b'$, $a' \geqslant a$ and $b' \geqslant b$, and an exit end measuring $a'' \cdot b''$, where $a'' < a'$ and $b'' < b'$, in particular, $a'' = b''$ and $a' = b'$.

The central portion of the radiation beam 12 entering the waveguide 11 passes therethrough without being reflected, whereas the peripheral portions of the beam 13 experience 1, 2, 3...p reflections in one plane and 1, 2, 3...q reflections in the other plane square with the former one. As a result, $(2p + 1) \cdot (2q + 1)$ radiation beams passes through the exit end of the waveguide, each of said beams filling the entire exit end, thus attaining uniform distribution of radiation energy density. The angular apeture (α_1, α_2) of the radiation beam emergent from the pyramid-shaped waveguide 11 equals to $\alpha_1 = 2p\beta_1$ and $\alpha_2 = 2q\beta_2$ in the meridional and sagittal

planes, respectively, where β_1, β_2 denote the apex angle of the pyramid in the meridional and sagittal planes, respectively.

The length ℓ of the waveguide 11 should obey both of the following conditions:

$$\ell \geqslant \frac{a' - a''}{2 \ \mathrm{tg} \frac{\alpha_1}{2}} ;$$

$$\ell \geqslant \frac{b' - b''}{2 \ \mathrm{tg} \frac{\alpha_2}{2}} .$$

As a result of an angular turn of the greater pyramid base in two mutually square directions round the centre '0', the incoming beam undergoes a certain new splitting into $(2p + 1) \cdot (2q + 1)$ elementary beams for every particular laser pulse, whereby there occurs additional equalization of radiation energy density in time.

Distribution of radiation intensity at the exit end of the pyramid-shaped waveguide results from interference of $(2p + 1) \cdot (2q + 1)$ light beams.

Now let us assess the period of the interference pattern, in view of which let us consider an interference of a radiation beam that has passed through the waveguide without being reflected from the walls thereof and that of a beam that has undergone one reflection from the lateral surface of a cone having an apex angle of β.

A distance between the adjacent maxima (minima) of

radiation intensity, i.e., the period $t = \frac{\lambda}{2\sin 2\alpha}$.

For the typical values of $\beta \approx 0.02$ to 0.04 and $= 193$ um the period t will be as follows:

$$t = \frac{0.2 \text{ to } 0.4}{2 \cdot 0.04} \leqslant 5\,\mu\text{m}.$$

Like in an embodiment shown in FIGS 1, 2, in the embodiment under consideration the scale of interference inhomogeneity of such an order is quite negligible for conducting ophthalmosurgical procedures.

An angular turn through a small angle γ of the order of 0.01 rad performed by the greater pyramid base round the point '0' results in a linear displacement of the edge of the exit end by a length of $\Delta(a")$

$$\Delta(a") = \frac{a"}{\cos\gamma} - a" \approx a" \frac{\gamma^2}{2},$$

where a" stands for the size of the exit end. With a"= 7 mm

$$\Delta(a") \approx 7 \cdot \frac{10^{-4}}{2} = 0.3\,\mu\text{m}.$$

The above value is quite negligible for ophthalmosurgery.

It is easily demonstrable that such oscillations of the waveguide entrance end will result in complete smearing of the effect of interference patterns from consecutive radiation pulses and, which is much more significant, in complete smearing of the effect of macroscopic inhomogeneity of the incoming laser beam.

CLAIMS

1. A device for ophthalmological laser surgery comprising a laser source, a beam distributor and a projecting lens, wherein the distributor comprises a waveguide.

2. A device according to claim 1, wherein the waveguide has a rectangular cross-section.

3. A device according to claim 1 or 2, wherein the distributor further comprises a lens to focus the laser emission into the the waveguide.

4. A device according to claim 3, wherein the focussing lens is adapted to oscillate normal to the path of laser emission.

5. A device according to claim 3 or 4, wherein the focussing lens has different focal lengths in the meridional and sagittal planes.

6. A device according to any preceding claim, wherein the waveguide is in the form of a parallelipiped.

7. A device according to any of claims 1 to 5, wherein the waveguide is in the form of a pyramidal frustum, the greater base facing the laser source.

8. A device according to claim 7, wherein the apex of the waveguide is adapted to oscillate about the path of laser emission.

9. A device according to any preceding claim further comprising a beam shaper.

10. A device for surgical treatment of ametropia, comprising the following components arranged on a common optical axis: a UV pulsed laser, a unit for uniform distribution of laser radiation energy density over the beam cross-sectional area, a shaper of required distribution of laser radiation energy density over the beam cross-sectional area, and a projecting lens, wherein the unit for uniform distribution of laser radiation energy density is a rectangular cross-section waveguide,

the device further comprising any, or any combination of, features as defined in any preceding claim.

11. A device for laser surgery comprising a waveguide, substantially as described hereinbefore, with particular reference to the accompanying Figures 1 and 2.

12. A device for laser surgery comprising a waveguide, substantially as described hereinbefore, with particular reference to the accompanying Figures 3 and 4.

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